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BEAM DUMP EXPERIMENTS AT THE AGS *

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Abstract

Searches for the prompt production of weak or semi-strongly interacting particles in a neutrino beam dump and their subsequent interaction or decay have been performed at the AGS. We detail the experiment using the totally active liquid scintillator detector, and mention the results of the spark chamber detector. An exposure of a copper beam dump to two orders of magnitude more protons than in previous searches at 28 GeV has yielded 104 neutrino-like events in the detector. The events from the beam dump are compared directly with those from π and K decay neutrinos produced concurrently in the normal long neutrino decay path following a 15 cm brass target. The characteristics of the events are similar. However, when compared to the rate of events predicted by scaling the 15 cm target yields, the beam dump data show an excess of 45^{+16} events. The excess events from the beam dump appear to deposit energies ≥ 1 GeV. Their source remains puzzling. Future experiments at the AGS could verify the existence of the effect, decrease the uncertainty in the predicted number of events from 30% to 10% by directly measuring the pion absorption length with a variable density target, search for threshold effects, and measure the sign of the charge of the exiting muons.

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A neutrino beam dump experiment has been performed at BNL in search of directly produced neutrinos, neutrinos from the decay of short lived parents ($\leq 10^{-11}$ sec), or new penetrating neutral particles. Protons of 28 GeV/c momentum are targeted on a Cu block in front of the massive, dense muon shield in the neutrino beam line of the AOS. The resulting π 's, K's, and hyperons are rapidly absorbed so that their decay to conventional neutrinos is strongly suppressed, facilitating the possible observation of other sources of neutrino-like events. To reduce the measurement to one comparing relative rates, we concurrently accept an equivalent number of conventional neutrino events by inserting a 15 cm brass block at the position normally occupied by the focusing horn and its neutrino production target.

Recent interest in this type of experiment has been heightened by the observation of the production of prompt ν_e and ν_μ events by 400 GeV protons on nuclei at CERN [1,2,3]. Among the possible sources for these events are:

- (a) the production and semileptonic decay of charmed mesons and baryons,
- (b) the production and decay of heavy leptons,
- (c) the production and subsequent interaction of light, penetrating particles, for example, the proposed semi-weakly coupled pseudoscalar boson[4] (the axion), and
- (d) the production and decay of new, short-lived light particles.

However, for source a) the production cross section ($\sim 30-100 \mu\text{b}$) appears to be large relative to the limits set by other searches for charmed particle production. Source b) would imply a neutral current to charged current ratio of $\sim 50\%$, which is not observed. The measured cross sections are too large for the axion (c) with properties as predicted in Reference [4].

Unlike the production of charmed particles or heavy leptons, production of short-lived light particles should not be strongly suppressed by decreasing the available center of mass energy (e.g. lowering the proton beam energy from 400 GeV to 28 GeV). Therefore, the results of a sensitive beam dump search for neutrino-like events at low energy may contribute to the understanding of the possible anomaly at high energies. Further, a low energy search can be more sensitive to certain channels, e.g. the axion, than searches at high energies.

A schematic layout of the experiment is shown in Fig. 1. The 28 GeV proton beam is transported in vacuum to a copper/brass beam dump 1.0m deep $\times$ 0.3m square in cross section followed by a 30m deep iron muon shield. Both the copper beam dump and the iron muon shield are stacked so that no cracks lie along the beam axis. A series of 22 radiation monitors along the proton vacuum pipe insure minimal beam loss upstream of the dump. A television camera monitors targeting accuracy by observing a flag on the front face of the dump. Ionization counters in the muon shield monitor the stability of the secondary particle flux.

To compare the beam dump events with events from π and K decay neutrino: a brass block, 15 cm long and 30 cm $\times$ 30 cm in cross section, is inserted 60 cm upstream of the dump; the beam pipe is partially removed from the decay space the 15 cm target runs. Exposures of 4.9×10^{18} protons on the beam dump and 2.0×10^{17} on the 15 cm target were registered by the outputs of current transformers at the end of the beam line. The readings of the radiation monitors, ionization counters, and current transformers are recorded on a pulse to pulse basis on the event tape.

Three detectors accepted events: the 7' bubble chamber, the aluminum spark chamber, and the liquid scintillator calorimeter. The last detector [5,6,7] (30T total, 11T fiducial), previously used in the $\nu_p \rightarrow \nu_p$ experiment, was triggered on events depositing $\geq 3\text{MeV}$ in the detector. We will discuss this experiment in detail, although the results from the spark chamber experiments are similar. To facilitate rejection of cosmic ray background, two 4-plane 4m $\times$ 4m drift chamber modules were installed horizontally above the calorimeter. Figure 2 shows the configuration of the apparatus.

A total of 7.2×10^4 (1.1×10^4) triggers are recorded during the beam spill on magnetic tape for the beam dump (15 cm target) runs. A software selection required a deposition of more than the 3 MeV threshold in three or more cells. The resulting 2700 (2500) events were written on a data summary tape and triple scanned by physicists to eliminate front entering particles and cosmic ray events. Front entering charged particles were rejected by requiring that no cell in the veto counter in front of the calorimeter or in the first active 40 cm of the detector have an energy deposition greater than 3 MeV. (A minimum ionizing particle deposits 35 MeV in a cell.) Cosmic ray events were identified by a topology or a time sequence of cell firings consistent with charged particles entering from above or behind the detector. The characteristics of cosmic ray events are known since the detector is enabled between beam bursts for a

period of time equal to the duration of the beam spill (3 μ sec every 1.2 sec). To minimize neutron-induced background in the eventual candidates for neutral current events, a minimum energy deposition of 160 MeV (a criterion found effective in past neutrino experiments with this detector) is also imposed.

From the remaining neutrino-like candidates, charged and neutral current events are identified on the basis of their topologies for each of the two targeting conditions. "Charged current events" are defined as those with at least one exiting, non-scattering, charged particle. The muon candidate must fire at least six cells (a range of ≥ 200 MeV) with a pattern of energy depositions consistent with that produced by a minimum ionizing particle. Figure 2 shows a typical charged current event (a $\nu_n \rightarrow \mu^- p$ reaction) which includes a stopping proton as well as an exiting muon. Approximately one half of the events have zero or one particle accompanying the muon; the other half have more than one additional particle. Events with no exiting particles (i.e., with no energy depositions above the 3 MeV threshold within 40 cm of any edge of the calorimeter) are classified as "neutral current events." A minimum configuration of three contiguous cells are required for these events. A total of 90 charged current events and 14 neutral current events are found in the beam dump runs, and 115 and 24 events, respectively, occur in the 15 cm target run.

The events in the above two categories for both targets exhibit all the characteristics expected of neutrino-induced events. The vertices of the events are uniformly distributed in the detector both along and transverse to the beam axis. The distributions of the angles of the particles produced in the reactions show no up-down or left-right asymmetries.

Charged-current neutrino events produced by π and K decays after the 15 cm target provide a time reference for the arrival of the neutrino bunches at the detector. Fig. 3b shows the time distribution of these events, modulo 222 ns, demonstrating a sharp timing structure ($\sigma = 17$ ns) for both neutral and charged current events. A window of 80 ns full width accepts all but one event. The beam dump data, Fig. 3a, is very similar. However, three events of the neutral current sample lie outside the timing window. These are presumably induced by slow neutrons or by cosmic rays. Assuming a uniform temporal distribution of these events, 1.5 of them lie inside the timing window and could be attributed to out-of-time background. We conclude that the background from slow neutrons and cosmic rays is at a negligible level, and that the 15 cm target data provides a valid sample of π and K decay neutrino events with which to compare the beam dump data.

To increase our sensitivity to neutral particles decaying in front of the detector by providing a longer observable decay path, and to quadruple our effective target mass for charged current neutrino events by using the concrete wall in front of detector as a target, we also accept the following two categories of events which have charged particles firing the veto counter in front of the detector:

- 1) Front entering horizontal muons. These events are required to have the time and energy deposition pattern characteristic of a muon as defined earlier. To discriminate against cosmic rays in this sample, the events must exit through the last module of the calorimeter.
- 2) External showers. These events have a vertex either in the calorimeter but outside the fiducial volume, or a vertex upstream of the calorimeter. The time distributions of both categories (1) and (2) of events are peaked in time with neutrino arrival at the detector, with no events occurring outside the 80 ns timing window. The angular distributions of the events relative to the beam axis show no asymmetries, either right-left or up-down. Further, the angular distribution of the front entering muons has the shape expected for muons produced by neutrinos interacting in the concrete wall. We conclude that these categories of events are beam associated.

A summary of the numbers of events in each category, after the few events occurring outside the 80 ns timing window have been removed and a background subtraction uniform in time has been made, appears in Table I.

Neutrinos from π 's and K's produced when upstream proton beam losses occur could contaminate the beam dump data. The radiation monitors continually record beam losses during the runs. The monitors are calibrated by producing known losses in the beam line by inserting flags (normally viewed by cameras to check the beam shape at various points in the line during beam tune up) in the beam at five points along the line. The flags typically produce beam losses of 1/4% to 1%, depending upon their thickness. A total exposure of 4×10^{16} protons on the targets produced no charged current events and one neutral current event in the detector. Typically two front-entering muon events are recorded for each target exposure. Comparing the output of the radiation monitors during the flag runs to that during the beam dump runs (typically a factor of 50) implies that <5 of the 104 neutrino-induced events in the beam dump run can be attributed to upstream beam losses. Further, there is no correlation between the rate of event occurrence and the periods of worst beam tuning conditions encountered in the runs.

We now have a sample of neutrino-like events that have their origin in the copper beam dump, as well as a sample of events induced by π and K decay neutrinos in the 15 cm target data. We attempt to isolate specific differences between the two samples that could point to non-conventional sources of neutrinos.

The interaction of new neutrinos in the detector could produce new heavy leptons which could decay into muons. Figure 4 compares the angular distribution of the muons from the beam dump with an equal number of events from the 15 cm target. The distributions show no differences. The shape of the 15 cm target data agrees with the calculated angular distribution (solid curve, Fig. 4b). The dashed curve in Fig. 4a shows, as a point of reference, the expected distribution for a heavy lepton of mass $1.8 \text{ GeV}/c^2$. There is no evidence for wide angle muons from such decays in the beam dump sample.

The production in the beam dump of heavy charmed hadrons and heavy leptons is expected to produce equal populations of ν_e and ν_μ induced events. However, electron showers are not easily distinguished from hadron showers in the

detector, especially since the average fiducial length is only 5 radiation lengths deep. Further, it is difficult to distinguish neutral current from charged current events if many tracks, i.e. high visible energies, are involved. Typically only neutral current events with low visible energies are totally contained and therefore unambiguously identifiable. The visible energy distributions for the neutral current events and for all events are displayed in Figure 5. Although the shapes of the data for the beam dump and 15 cm runs are similar, the beam dump spectrum appears to be somewhat more uniform.

A possible signal for new neutrinos would be an enhanced neutral current to charged current ratio in the data. Such an enhancement could also be produced by axions, which are expected to couple to the π^0 , giving rise to an excess of neutral current Δ production events. The neutral to charged current ratios, R, for beam dump and 15 cm target,

$$R^{BD} = 0.16 \pm 0.04 \quad \text{and} \quad R^{15\text{cm}} = 0.21 \pm 0.05,$$

show no evidence for an excess of events in the beam dump runs.

We also check for an excess of neutrino-like events above that attributable to neutrinos from the decay of π 's and K's in the short length before absorption in the dump. Table I shows the ratio F,

$$F = (\text{Event Rate from 15 cm Target}) / (\text{Event Rate from Beam Dump})$$

for the four event categories. Note that for neutrino-induced events in the detector (the sum of charged current and neutral current events), the ratio is

$$F = 33 \pm 4.$$

A superficial calculation suggests that the event rate is proportional to the neutrino flux, ϕ ,

$$\phi \propto D \times TE \times \Omega,$$

$$D = 1 - \exp(-L/7.1 \text{ m } \lambda\gamma),$$

where L is the length of the decay path for π 's; TE is the proton targeting efficiency i.e., the fraction of protons that interact in the target before exiting; and Ω is the solid angle subtended by the detector. Appropriate values for these parameters are the following:

	L	TE	η
15 cm Target	60m	64%	$(1/135m)^2$
Beam Dump	0.29m	100%	$(1/105m)^2$

For $\langle \beta \gamma \rangle = 20$, which is appropriate to the pions producing neutrinos of the energies we observe, we obtain an estimate of the ratio of event rates,

$$F = 67.$$

We have performed a simple numerical integration to calculate the relative rates, including the differences between the beam dump and the 15 cm target in the following respects:

- beam divergence
- pion absorption in the 15 cm target
- pion absorption in the air of the decay space
- proton production of pions in the air decay space
- multiple scattering of the particles in the 15 cm target, and
- the multiplication production in the beam dump.

The calculation yields

$$F = 57 \pm 12.$$

The sensitivity of F to each of the above factors and to the input parameters and the best estimate of our knowledge of each of them is tabulated in Table II.

Let us discuss the most poorly known (and the most important) parameter in our rate estimate, the "effective pion absorption length" in the forward direction in a dense target. This number includes the effects of secondary pion production (and is therefore larger than the normal pion absorption length defined for thin targets). This number was measured in the only previous low energy (26 GeV) beam dump experiment (at Cargamelle [8] in 1972). From the distribution of muons in the muon shield (a measurement calibrated with nuclear emulsions to 7%) the effective pion absorption length [9] in mercury is measured to be 25 ± 8 cm. We assume that the effective pion absorption length scales as the normal pion absorption length. The cross sections are known to scale as $A^{0.75}$ and the absorption length depends inversely on the density. This

yields 29 ± 9 cm for the effective pion absorption length in copper. (For comparison, the normal pion absorption length is measured [10] to be 16.5 $\pm$ 0.6 cm in Cu at $\langle E_\pi \rangle = 6$ GeV, the mean energy for pions producing neutrinos of a mean energy of $\langle E_\nu \rangle = 1.5$ GeV.) Direct measurement [11] in an iron calorimeter exposed to 200 GeV incident particles, where multiple pion production should certainly be important, yields an absorption length of 230 gm/cm^2 (≈ 29 cm).

We expect a ratio F of 57 ± 12 and observe a value of 33 ± 4 . For the 139 neutrino-induced events observed in the normalization run (2×10^{17} protons on target) with the 15 cm target, we would predict for the beam dump run

$$N^{\text{predicted}} = 59 \pm 13 \text{ events.}$$

We find

$$N^{\text{observed}} = 104 \pm 10 \text{ events}$$

for 5×10^{18} protons on target. The excess beam dump events that could be attributed to new processes is

$$N^{\text{excess}} = 45 \pm 16 \text{ events.}$$

As an independent check of the above prediction, we have extensively studied cascades using a Monte Carlo method. The input [12] are the actual showers generated to simulate hadron cascades in iron calorimeters initiated by either 28 GeV protons or by neutrinos producing showers of similar energy. The spatial and energy distributions derived from these calculations are known to fit [12] the data to $\sim 5\%$. The pions of the cascade are allowed to decay within the beam dump or the 15 cm target, or after the 15 cm target in a volume the size of the BNL tunnel. The shower development in the beam dump exhibits a 29^{+4} cm effective pion attenuation length, consistent with the Cargamelle measurement. The program yields

$$N^{\text{predicted}} = 57^{+4} \text{ events,}$$

where the error is determined by the known uncertainty in agreement between previous calculations with this program and hadron absorption experiments. Again the prediction is in agreement with the number calculated earlier. If this is taken at face value, the 3 standard deviation excess becomes a 4.5σ effect.

The visible energy distributions predicted by the cascade calculation have proportionately more low energy events in the beam dump case than in the 15cm one, because (1) pion scattering in the dump degrades the pion energy, (2) the multiple pions that are produced have lower energies, and (3) the smaller source to detector distance for the dump means that larger angle, lower energy pions contribute to the neutrino events at the detector. The excess events appear to deposit total visible energies ~ 0.5 to 1.0 GeV. This is opposite to the effect we would expect from an underestimated multiplication contribution or an excess of background events, both of which populate low energies.

If we assume that the excess events arise from promptly produced neutrinos, then

$$B\sigma_p\sigma_i = (1.8^{+0.4}) \times 10^{-69} \text{ cm}^4/\text{nucleon}^2,$$

where B is the branching ratio into ν_μ , σ_p is the production cross section of neutrinos into a 10mrad acceptance in the forward direction, and σ_i is the interaction cross section. For neutrinos interacting with $\sigma_i = 10^{-38} \text{ cm}^2/\text{nucleon}$,

$$B\sigma_p = (1.8^{+0.4}) \times 10^{-31} \text{ cm}^2/\text{nucleon}.$$

We observe the same ratio of neutral current to charged current events in the beam dump and in the 15 cm target runs. Thus we see no anomalous π^0 production which might be attributed to axion-induced events. This allows us to set a limit on the product of the cross sections for the production and subsequent interaction of axions. Our measurement,

$$\sigma_p\sigma_i < 10^{-69} \text{ cm}^4/\text{nucleon}^2,$$

is an order of magnitude better than previous limits [4,13]. In terms of the coupling η of an axion to matter relative to that coupling for the π^0 ,

$$\eta < 0.5 \times 10^{-9}.$$

Concurrent with our running the Columbia - Illinois - R.N.L. collaboration also took data. Their detector has a smaller mass (~ 5 tons) and a slightly greater angular acceptance (Fig. 1). The results of their run are presented [16] in Table III. Note that they have muon charge identification and some evidence on the presence of electrons. Their event rates and observed beam dump to bare target ratio are similar to our own.

A beam dump experiment [14] similar to ours has been performed at Surpukov with 70 GeV protons. An excess number of neutrino events has been seen there also, but the error bars are large enough to accommodate our observation either with no energy dependence or with the energy dependence observed in Ψ/J production.

An additional exposure of 10^{19} protons on target (pots) could resolve the issues presented above and elsewhere [15]. The run could include the following elements, where approximate fractions of the total pot request used in each study appear in parentheses:

1.) Measure directly the effective pion absorption length by using a variable density copper target and extrapolating to infinite density (1/2, 1/3, and 1/6 of the pots at full, half, and a third density, resp.). A 10% measurement is anticipated.

2.) Measure the effective pion absorption length by measuring the number and spatial distribution of muons in the dump with the existing fixed and traversing ionization chambers. The distribution of charged particles in the dump from our Monte Carlo program and the systematics inherent in a foil calibration suggest that a 10% measurement is realistic.

3.) Raise the proton energy from 28 GeV to ~ 31 GeV to search for threshold enhancements indicative of heavy particle production. Such a change would increase the production of heavy particles but would leave the rate for light particles unchanged. (1/2 pots).

4.) Operate the muon spectrometer during this run to ascertain if the excess events are associated with an anomalous μ^+/μ^- ratio.

TABLE I
A SUMMARY OF EVENT STATISTICS

	<u>Beam Dump Runs</u>	<u>15 cm Target Runs</u>	<u>Ratio of Event Rates</u>
Protons on Target $\times 10^{17}$	48.7	2.0	(15cm Target Rate Beam Dump Rate)
Event Category:			
Charged Current Events	90	115	32^{+4}_{-4}
Neutral Current Events	<u>14</u>	<u>24</u>	42^{+14}_{-14}
Total Neutrino Events in Detector	104	139	33^{+4}_{-4}
Neutral Current Events/ Charged Current Events	0.16 ± 0.04	0.21 ± 0.05	
Front Entering Muons ⁺	162	314	40^{+4}_{-4}
External Showers ⁺	65	97	31^{+5}_{-5}

⁺Protons on target in the beam dump runs for these events = 40.4×10^{17} .

Table II

Sensitivity of Ratio F of Rate of 15cm Target Events
to Beam Dump Events to Various Input Parameters

<u>Input Variables</u>	<u>Beam Dump</u>	<u>15cm Target</u>	<u>Change in F for +1σ Variation in Variable</u>
Decay length folded with multipion production ("Effective Pion Absorption Length")	29^{+9}_{-9} cm		-25%
Decay Length		60 ± 0.5 m	+0.6%
Detector distance		165.3 ± 2 m	
Detector distance	105.5 ± 2 m		+1%
Targeting Efficiency		0.65 ± 0.04	+2%
Beam Divergence			
Horizontal	0mr	1.9mr	
Vertical	0.14mr	$3.2 \text{mr} \pm 0.3 \text{mr}$	+0.5%
Transmission of π's in Cu Absorption of π's in Air of Decay Space		0.805	
Production of π's in Air of Decay Space		1.03	0%
Multiple Scattering in target of π's		10mr	0%

TABLE III
COLUMBIA - ILLINOIS - BNL BEAM DUMP RESULTS[16]

	Beam Dump Runs	15 cm Target Runs
Raw Events		
Charged Current Candidates	55	54
Neutral Current Candidates	21	10
Timing Cut and Subtraction		
Charged Current Candidates	49	53
Neutral Current Candidates	14	9
Topological Cut		
CC 23 Prongs Charged Current Candidates	29	24
NC 22 Prongs Neutral Current Candidates	14	9
Electron Candidates	1	1
Charge Ratio	$19\mu^-/6\mu^+$	$19\mu^-/4\mu^+$

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SCHEMATIC LAYOUT OF BNL BEAM DUMP EXPERIMENT

Fig. 1 Schematic layout of the BNL neutrino beam line with the two configurations discussed in this paper, the 15 cm target and the beam dump target.

Fig. 2 Side view of the target detector showing a typical charged current event superimposed on it. The energy deposition in MeV is indicated on the cells that fired and the positions of drift chamber hits are marked.

EVENT TIME DISTRIBUTIONS MODULO 222 ns

Fig. 3 Distribution of event times for charged (CC) and neutral current (NC) events observed during beam dump and 15 cm target exposures.

Fig. 4 Muon angle distributions for samples of charged current events from both the beam dump and the 15 cm target.

VISIBLE ENERGY DISTRIBUTIONS

Fig. 5 Visible energy distributions for neutral current (NC) and charged (CC) events in both beam dump and 15 cm target runs. (The energy deposited by the existing muon while traversing the detector is typically 200 MeV.)